A Bursting Landscape in the Middle of Portugal: Theories and Experiments by Georges Zbyszewski

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Abstract. During the 1930s, the Portuguese dictatorship known as *Estado Novo* was determined the country should become industrialized, and one of the favoured economic sectors was mining. Therefore, the Service for Mining Prospecting was created in 1939, a public institution which was in charge of surveying and researching mineral resources. It was in this context that in 1946 Georges Zbyszewski (1909–1999), a French geologist working for the Portuguese Geological Survey, was entrusted with the supervision of geological work in a region of central mainland Portugal, known as the typhonic valley. In order to be able to make a complete study of the geology of the region, Zbyszewski needed to know the origin of the typhonic valley, and so he carried out some experiments with analogue models. Zbyszewski was the first geologist in Portugal to use analogue models in geological research, which seems to have been down to his early practice in France. Although, this use of analogue models in the context of experimental geology turned out to be a timely and idiosyncratic attempt with no real consequences for the practice of Portuguese geology at the time. Almost 40 years had to pass until Zbyszewski's pioneering work could bear fruit.

Keywords. Analogue models, experimental geology, Georges Zbyszewski, Portugal, typhonic valley

1. Introduction

In her most recent book devoted to experimental geology, Newcomb argues that its contribution to the establishment and development of geology was far more significant than it has usually been considered (Newcomb, 2009, xiii, p. 171). Historians of science in general, and particularly of geology, have paid little attention to the role of experiment in geological practice, something which fits with the lack of significance many geologists, themselves, attach to experimental geology. For many geologists and historians of geology, contrary to what happens in most of the natural sciences, experiment is not considered a distinctive feature of geological practice; it is fieldwork that matters (Newcomb, 2009, xi–xiii, pp. 171 and 172). Besides, experimental geology has been, since its beginning, a controversial issue, in which the strong empirical discourse of the first generations of geologists puts in check the validity of the results obtained. From the

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perspective of the former, experimentation was inevitably related to the formulation of hypotheses, which, in turn, raise important methodological questions: during an experiment it is possible to demonstrate that a certain hypothetical cause can produce a certain effect, but it cannot unmistakably prove that a cause-effect relation took place (Oreskes, 2007, pp. 94 and 95).

Historical literature devoted to experiment in geology has focused mostly on the chemical and mineralogical traditions of the discipline, on the use of instruments in geological practice, and on certain specialities which have more explicitly instrumental and quantitative characteristics, like geophysics.[1] A survey of the literature makes quite clear the near absence of studies on the use of models in geology, even though they have played an important role in the development of this science since the 19th century, and have simultaneously had a meaningful importance as didactical tools. Oreskes is one of the few authors who has dedicated some work to this topic, her most recent study about the use of models in the earth sciences in the 19th and 20th centuries being noteworthy. Oreskes points out how, starting in the second half of the 20th century, the use of simulations in computers in geology brought a new meaning to the word 'model,' at the same time as its purposes, as well as the epistemic and methodological questions coming along with its use, were redefined (Oreskes, 2007).

This study aims to improve understanding of the role of analogue models in geological research. The first experiments carried out in Portugal using this kind of models will be described, as well as the circumstances surrounding their occurrence. This study will also provide us with an insight into how Georges Zbyszewski (1909–1999), a geologist of the Portuguese Geological Survey (PGS) (*Serviços Geológicos de Portugal*), developed his work in experimental geology, and as such it constitutes a case study of the methodologies used during geological research.

The experiments considered were performed by Zbyszewski during the 1940s, as part of a more comprehensive study of regional geology, which the geologist developed in one of Portugal's geologically most complex regions, the typhonic valley ('vale tifónico' in the original). Georges Zbyszewski, a native Russian with French citizenship, was contracted as a PGS geologist in 1940, following various geological travels in Portugal. Zbyszewski would remain in the country for the rest of his life, always working for the PGS (Teixeira, 1984a, pp. 13–22; Teixeira, 1984b, pp. 23–43; Ribeiro, 1984, pp. 55–72).

As will be seen, Zbyszewski's design, construction and use of analogue models was meant to discover the main factors underlying the formation of the typhonic valley, by the choice of one among several hypotheses. Only then would the geologist be able to reconstruct the geological history of the region he was studying.

However, Zbyszewski's use of analogue models in an experimental context had no immediate consequences in Portugal and ended up as an idiosyncratic and localized investigation. Zbyszewski's initiative appears to be rooted in his earlier geological training, in a certain way of practicing geology, which he left behind when he decided to live in Portugal. It wasn't until the 1980s that Portugal had a sound school of experimental geology based on the use of analogue models.

2. The Region of the Typhonic Valley, in the Centre of Mainland Portugal

In 1944, a private company called *Companhia de Sais de Potássio Lda.* asked the Portuguese government to survey and prospect for rock salt and potassium salts in a region geologically known as the 'typhonic valley,' situated in central Portugal. The governmental institution in charge of this type of work was the Service for Mining Prospect (SMP) (*Serviço de Fomento Mineiro*), created in 1939 with the purpose of carrying out the survey and prospecting of mineral resources existing in mainland Portugal (Law no. 29,725, 28 June 1939). The SMP was also seen as a way of promoting industrialization in the 1930s by the *Estado Novo*—the dictatorship then ruling Portugal—which aimed at the development of various productive activities, among them the mining industry (Medeiros, 1978; Miranda, 1987, pp. 41–65; Brandão de Brito, 1988, pp. 209–234; Brandão de Brito, 1989). After the establishment of the SMP, mining activity increased in Portugal, and the organization was also able to offer support to private companies.

In the case of the request made by *Companhia de Sais de Potássio Lda.* it was clear that the SMP would need to provide an experienced geologist to support the survey and prospecting requirements. This led the SMP management to approach the PGS regarding cooperation. Both institutions were part of the General Directorate of Mines and Geological Survey (*Direcção Geral de Minas e Serviços Geológicos*). Georges Zbyszewski, who was then the PGS sole geologist, was the person put officially in charge of following up the activities of the SMP in the region of the typhonic valley (Zbyszewski, 1959, pp. 7 and 8).

The typhonic valley is located near the town of Caldas da Rainha and is about 30–35 km long, oriented NE-SW. The word typhonic[2] was probably used for the first time in Portuguese geological literature by Paul Choffat (1849–1919)—a Swiss geologist who worked for the PGS between 1878 and 1919—to name special kinds of tectonic events and structures that nowadays geologists assume to be related to diapiric phenomena[3] (Choffat, 1881–1882, p. 266). In geology, the term is applied to geological/structural processes related to the up rise and/or extrusion of eruptive or plastic materials, like gypsum, rock salt and clays, which, when compressed at depth, move towards the surface. The occasional extrusion of these materials, normally presented as violent and abrupt, happens, in fact, gradually. This process, however, always causes the deformation of the overlaying layers, which take the appearance of having been 'broken' as a result of some violent action (Choffat, 1881–1882, p. 266).

The typhonic valley is composed of a central nucleus in anticline, which occupies almost all the bottom of the valley and includes intensively folded marls, as well as salty and gypsiferous clays of Hettangian age (Figure 1).[4] Moving towards the sides

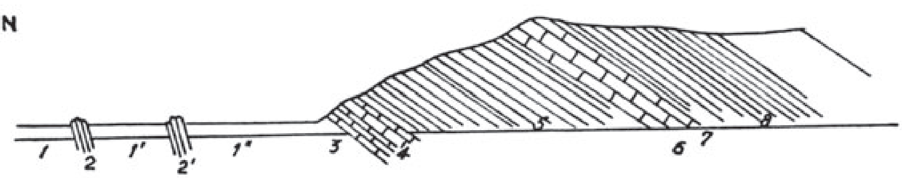


Fig. 1. Geological section of the typhonic valley. 1,1′,1″—Lower Jurassic marls; 2,2′,3—Lower Jurassic limestones and dolomitic limestones; 5–8—Jurassic/Cretacic limestones and sandstones (adapted from Zbyszewski, G. (1959) Étude structurale de l'aire typhonique de Caldas da Rainha, *Memórias dos Serviços Geológicos de Portugal*, 3, Nova Série, planche C).

of the valley, marls and clays become less deformed and 'dive' discordantly under the older surrounding formations. At some points of the central nucleus, layers of dolomitic limestone presenting strong dip can be found, whereas the same layers, when near the border of the valley, show the same dip as the surrounding formations. The marls/clays/dolomitic limestone located at the bottom of the valley, are of Lower Jurassic age and are intensively eroded and covered by Pliocenic and Quaternary deposits. They are crossed by numerous doleritic domes and veins, and, at a number of places, by tectonic structures transversally crossing the valley, their presence being marked by salty and sulphurous water sources (Zbyszewski, 1947, pp. 241 and 242).

The geological formations around the valley are composed of Jurassic/Cretacic limestone and sandstones, and are therefore younger than the bottom of the valley. The contact between the rocks of Hettangian age in the nucleus of the valley and the Jurassic/Cretacic formations around it is, in most cases, discordant (Zbyszewski, 1947, p. 242).

The typhonic area forms an independent tectonic unit, in which the Lower Jurassic central nucleus was deformed in a different manner from the Jurassic/Cretacic surrounding formations. The subsequent action of the erosive agents caused a differential erosion of the more plastic formations of the nucleus of the valley, leaving at higher elevations the more resistant Jurassic/Cretacic formations that surround them. Zbyszewski explained in this way the constitution and evolution of the typhonic valley. His explanation was constructed upon data obtained from geophysics, drilling, and geological fieldwork but also by taking into account the stratigraphic units then accepted by the geological community. Zbyszewski, however, was plagued by doubt regarding the origin of the typhonic valley and he decided to carry out some experiments (Zbyszewski, 1959, pp. 9 and 10).

3. *Hypotheses on the Origin of the Typhonic Valley*

A variety of geologists working at the PGS, like Carlos Ribeiro (1813–1882), Nery Delgado (1835–1908) and Paul Choffat studied the typhonic valley. Following Choffat's death, in 1919, the PGS technical staff did not study this region in detail, in part, due to the PGS' decline over the first three decades of the 20th century (Mota, 2007a,b; Carneiro and Mota, 2007). It was only during the 1930s and 1940s that the typhonic valley was once again studied by the Portuguese geologists Carlos Freire de Andrade (1893–1956) and João Carrington Simões da Costa (1891–1982). These geologists who studied the typhonic valley suggested some hypotheses about its origin, but none of them were particularly innovative. Most of their ideas followed closely those traditionally supported by the international geologic community, and, furthermore, none of the Portuguese geologists carried out detailed geological studies that would have allowed them to test such hypotheses.

Choffat postulated that the typhonic valley was formed from a fracture existing in the upper formations, and that the opening of the fracture border allowed the rise of the lower formations. This rise of the lower formations would result from the vertical pressure exerted on them by the upper ones (Choffat, 1883–1887). Choffat's hypothesis seems to combine the mechanism proposed by Willem van der Gracht (1873–1943)—in-depth plastic formations move towards the surface in places where coverage is more fragile—with the buoyancy hypothesis, widespread during the first three decades of the 20th century, and which held that the pressure exerted by the upper geological formations on the lower plastic ones caused the rise of the latter (Jackson, 1995, p. 4; van Veen, 2001, p. 434).

Freire de Andrade suggested that tectonic structures similar to the typhonic valley were associated with the existence of horizontal forces caused by orogenic movements.[5] Owing to such laterally exerted forces, more or less complex fault systems were formed, with the rupture of the anticline and the overlapping of the occidental border on top of the oriental one. This process was accompanied by the injection of plastic materials existing at depth (Freire de Andrade, 1933). Freire de Andrade's hypothesis is a version of the regional contraction hypothesis put forward by Hans Stille (1876–1966) (Jackson, 1995, pp. 4 and 5).

Given the associated occurrence of deposits of rock salt and potassium, Carrington da Costa believed that the origin of the typhonic valley could be explained in the broader context of diapiric phenomena. He advocated that lateral pressures had caused the assembled displacement of the upper formations, which were then folded and fractured. The rise of the marls and clays that made up the central nucleus of the valley was due to their lower density, when compared to that of the overlying layers. The existence of fractures and the erosion of the upper formations had facilitated the uprising (Carrington da Costa, 1944). The hypothesis proposed by Carrington da Costa seems to be a combination of several ones advanced by foreign authors to explain phenomena related to diapirism (Jackson, 1995, pp. 4–7).

These were the main hypotheses put forward by the Portuguese geologists to explain the origin of the typhonic valley when, in 1944, Georges Zbyszewski started to work in the area. After his field surveys, and by adding them to the data obtained from reading and interpreting the results from drillings and geophysical prospecting, Zbyszewski elaborated his own idea on the origin of the typhonic valley, admitting that it was related to a context of salt/diapiric tectonics that had taken place between the Jurassic and the Pliocene. Despite the fact that Zbyszewski found it probable that in such a context vertical movements were predominant, he still wondered about the possibility of lateral movements having occurred and about the role they might have played in the process (Zbyszewski, 1947, p. 249). Zbyszewski's doubts were pertinent, not only because it was possible to admit the two types of movement in Portuguese tectonics (Zbyszewski, 1947, p. 247),[6] but also because many geologists postulated that lateral pressures, may, play a meaningful role in various contexts of diapirism (Jackson, 1995, p. 4).[7] He then decided to conceive and carry out a series of 'laboratory experiments' that would allow him to verify the 'mechanism by which typhonic valleys could have been formed' and clarify 'the role of the main factors that were involved in its origin [of the typhonic valley]' (Zbyszewski, 1947, pp. 247–249). He meant by 'main factors' the type of forces exerted and the movements they produced.

By using easily available materials whose behaviour, when subjected to pressure, was similar to that of the real geological formations, Zbyszewski conceived and built a set of models and carried out a series of experiments which reproduced the conditions postulated in various hypotheses concerning the origin of the typhonic valley. In all of them he used clay from the Tagus River to represent the Hettangian marls and clays. The layers of dolomitic limestone interposed in the marls and clays were represented by sheets of paper. A mixture of plaster and kaolinite, hardened but sufficiently plastic to be deformed under the action of the pressures applied, represented the upper, more rigid Jurassic and Cretacic formations. Since Zbyszewski's models were built using materials whose rheological[8] behaviour was similar to those of the real geological formations, they are called analogue models (Zbyszewski, 1947, p. 252).

4. Models in Science: The Philosophical Approach

'They [models] variously purported to bring the tiny, the huge, the past, or the future within reach, to make fruitful analogies, to demonstrate theories, to look good on show' (Hopwood and Chadarevian, 2004, p. 1).

Since the 19th century, philosophy of science has focused on the role played by models in science, in particular in the interpretation of data, the structure and justification of theories, and the question of scientific realism (Morgan and Morrison, 1999a, pp. 1–3; Hesse, 2000, pp. 299–301). In broad terms, the two most traditional approaches are the semantic and the analogical conception of theories. The semantic one, formal and a-historical, defines a model as being one of the entities that satisfies the formal axioms of a theory, the latter being considered to be a set of models plus its formal structure. This perspective establishes a clear distinction between theory, models and the data derived from observation and experiment (Morgan and Morrison, 1999a, pp. 3–5; Hesse, 2000, pp. 306 and 307).

To a great extent, the analogical conception regards theories as constituted by hypothetical or analogue models of reality, and not by formal systems. According to this approach, a model somehow represents the structure and the behaviour of a given physical object/system. The relationship between the latter and the model presents, characteristically, different types of analogies (Morgan and Morrison, 1999a, pp. 5–7; Hesse, 2000, p. 307). This approach arose from the need to link philosophical accounts of models with their real use in scientific practice and was extensively discussed by Hesse (Hesse, 1966).[9]

Theory is always the starting point from which to think about models, which are mainly considered objects of transition between theory and a given physical object/system, regardless of the approach adopted. Recent developments in the history and philosophy of science have come to show that this conceptual framework is no longer adequate for a more thorough and meaningful understanding of the role of models in science (Armatte and Dahan, 2004). The processes of constructing and handling models have been shown to be crucial for the understanding of scientific practice, providing information about scientific theories, the world and models themselves. According to this perspective, models, even if they are not completely independent in relation to theories and the world, do present a certain degree of autonomy, which allows them—and is, in fact, a necessary condition—to act as mediators between them. The autonomy presented by models arises from the fact that their construction does not depend, exclusively, either upon the theory or upon the data, but, instead, upon the combination of both and even upon the incorporation of other elements (Morgan and Morrison, 1999b, pp. 10 and 11). The condition of models as autonomous agents of scientific practice also allows them to function as instruments with a diversity of functions in the course of such practice (Morgan and Morrison, 1999b, pp. 10 and 11).

5. *Tridimensional Models in Science*

Some types of models have received little attention from philosophers and historians of science. Theoretical models, ‘abstract objects, imaginary entities,’ (Giere cited in Hopwood and Chadarevian, 2004, p. 2) have been receiving more attention than those that are constructions in a more literal sense and made of materials such as ‘spring washers, magnets, lots of tin foil and such’ (Hacking cited in Hopwood and Chadarevian, 2004, p. 2). Despite the existence of various recent studies on representation in science, they all tend to downgrade the importance of three-dimensional models, focusing their attention on the way scientists discipline Nature by reducing the tridimensional to two dimensions: ‘There is nothing as easy to dominate as a plane surface’ (Latour cited in Hopwood and Chadarevian, 2004, p. 2). On the other hand, many tridimensional models are considered to be of only secondary interest, since they are taken as being more related to teaching and to the popularization of science than to scientific practice and research. Recent literature has shown the flaws of this approach since models often start out as research tools and then become teaching aids; conversely, models used for teaching often end up influencing scientific research (Hopwood and Chadarevian, 2004, p. 3).

Scientific tridimensional models started to be constructed and used in Western Europe and in the USA around the mid-18th century, where they were exhibited in studios, academies, societies, and lectures or at the newly created museums (Hopwood and Chadarevian, 2004, p. 4). During the 19th century, with the institutionalization and teaching of science becoming increasingly widespread, tridimensional models came to be widely used as didactical objects, while at the same time, in some areas, scientific practice discovered the crucial importance of their use. Simultaneously, models came to play an important role as mediators between science and a more general cultural context, as witnessed by their presence in public lectures and in international exhibitions around the turn of the 19th and 20th centuries (Hopwood and Chadarevian, 2004, pp. 5 and 6).

During the 20th century, various types of tridimensional models saw their importance and use decline in some scientific areas, both as didactical objects and as instruments connected to scientific practice. In other areas of knowledge, however, exactly the opposite happened, as shown by the importance of models in the development of molecular biology. In the past few decades, computer simulations, together with interactive displays, have been meaningfully changing—and may even come to dominate—the construction, use, and significance of tridimensional models in science (Hopwood and Chadarevian, 2004, pp. 7 and 8).

6. The Use of Tridimensional Models in Geology: Analogue Models

The majority of the geological processes occur on spatial and temporal scales that do not allow their full understanding by those who study them. Furthermore, many of the processes happen at inaccessible places of the Earth, and reconstructing the way in which they occurred in the past is hindered by a series of circumstances, like the lack of outcrops and limitations of the existing technology, among others. In order to try to overcome these restraints, geologists make use of models in their experiments, which could be handled by humans and had manageable spatial and temporal scales. These models could then simulate, on a reduced scale and in a simplified way, larger and more complex geological structures and processes, so offering a way ‘to access the inaccessible’ (Buiter and Schreurs, 2006, vii; Oreskes, 2007, p. 93).

Despite being impossible to simulate exactly in detail geological structures and processes identical to the real ones, geologists nowadays agree that, if the materials used in models have a rheological behaviour similar to real geologic materials, it is possible to reproduce the most important characteristics of geological structures and processes (Belousov and Gzovsky, 1965). In geology, models with these characteristics are called analogue models, and a judicious choice of the materials and of the conditions they are subject to may lead them to approach scale models, in which the quantitative relationship between physical properties is proportionally related to the real geological situation (Hubbert, 1937, 1945; Oreskes, 2007, pp. 110–113).[10]

Most analogue models have been used in experiments intended to demonstrate the causal efficacy of a specific agent. The initial stages of models can be compared with their later ones after the proposed agent has been put into action, and the comparison is essential to gain an understanding of the evolution of geological processes and their resulting structures (Buiter and Schreurs, 2006, vii; Oreskes, 2007, p. 93). The main methodological concerns regarding the use of analogue models are scaling problems—is it really possible to reproduce the earth's features and its dynamics on a human scale?—and the problem of hypothesis (Oreskes, 2007, p. 93).

Analogue models have been used in geological research since the 19th century, mainly to investigate tectonic and geomorphologic structures and processes (Oreskes, 2007, pp. 94–113). In the first decades of the 20th century, their use in the broader context of experimental geology was well established. The improvement of methods and techniques, the development of experimental systems to enlighten a wider diversity of processes, and the search for the use of more suitable materials, became the major trends in geological research's use of analogue models. Nowadays, it is possible to produce a plethora of models that simulate both processes—crustal isostasy, rift valleys, the growth of continents—and structures—glaciers, plutons, diapirs. Another recent trend in analogue modelling involves the complementary use of numerical computer simulations and/or the replacement of analogue models by those simulations (Talbot, 2001, vii–ix; Koyi, 2007, pp. 224 and 225; Oreskes, 2007, p. 113).

Oreskes argues that this led to a change in the purposes of models and in the methodological concerns that arose as a consequence of their use. Contrary to what happened with analogue models, which were mainly intended to demonstrate causal efficiency, computer simulations now attempt to predict the future behaviour of geological systems and methodological concerns are now associated with confirming or denying such predictions. As a consequence, the word 'model' has changed its meaning in geology and the epistemic values of its practitioners have also changed. This latter change came with the geologists' enrolment in the task of prediction, which was mostly an imposition from outside the geological community. In fact many geologists continue to doubt the role of prediction. As Oreskes puts it: 'The shift toward prediction (. . .) was not primarily a manifestation of the epistemological aspirations of earth scientists. (. . .) The rise of prediction was a response to the needs and aspirations of patrons' (Oreskes, 2007, pp. 93, 119 and 120).

7. Georges Zbyszewski's Experiments with Analogue Models

In a paper published in 1947, 'Essai d'étude expérimentale sur les phénomènes typhoniques,' Zbyszewski describes in detail the experiments he performed using analogue models, namely the materials used for the construction of the models, the experimental procedures taken while testing the hypotheses, the results obtained, and their interpretation. He accompanies the description with a series of photographs and sketches (Zbyszewski, 1947, pp. 249–276). The photographs show the results obtained in each experiment and the sketches are a visual representation of the hypotheses tested. There is a strong connection between the sketches and the descriptions of the experiments, making them more than a mere illustration of hypothetical structures and processes. Sketches and descriptions support each other, they complement each other, making the whole intelligible.[11]

For each one of his experiments, Zbyszewski placed the materials used in a box according to the following disposition: an irregular layer of plaster covering the bottom of the box to represent the substratum; interposed layers of clay and sheets of paper, with different thicknesses, representing the complex of marls, clays, and dolomitic limestone, which constitute the lower, more plastic Hettangian formations; a compact layer of a mixture of plaster and kaolinite representing the upper, more rigid formations of the Jurassic/Cretacic. Due to the dimensions of the box, this last layer was not sufficiently thick; different weights were placed upon it, according to the hypothesis being tested, in order to simulate the pressure conditions prevailing in each hypothesis. Vertical forces were definitely favoured in the majority of the experiments (Zbyszewski, 1947, pp. 252 and 253).

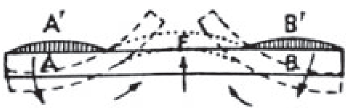
Table 1 summarizes the hypotheses tested during the experiments and the results obtained at the end of two of them can be seen in Figure 2 (Zbyszewski, 1947, pp. 249–276).

After analyzing and interpreting the results of each of his experiments, Zbyszewski complemented them with the interpretation of data obtained during his field surveys, drillings and geophysical prospecting. It was then possible for him, by eliminating the others, to choose one of the hypotheses as being the most probable way to explain the origin of the typhonic valley, a methodological procedure usually known as 'the method of multiple working hypotheses' (Chamberlin, 1890). According to Zbyszewski, this hypothesis was the one tested in the second experiment, namely, the hypothesis postulated by Choffat with a prominence of vertical movements, but Zbyszewski placed the proposed mechanism in a wider context of salt/diapiric tectonics, in which the role played by large-amplitude lateral pressure is negligible, but the role of more localized lateral pressure should be taken into account. By combining and interpreting the data obtained by the use of various techniques and methodologies, Zbyszewski was able to reconstruct a geological history of the typhonic region of Caldas da Rainha (Zbyszewski, 1947, pp. 285–294; Zbyszewski, 1959, pp. 123–127).

The use of analogue models in the experimental context envisaged by Zbyszewski is of particular relevance because they have a high representative value: they simultaneously represent a geological structure—the typhonic valley—a given geological process—the formation of that valley—and a set of theoretical statements—the hypothesis about the origin of the valley. That representative value came from the fact that the construction of

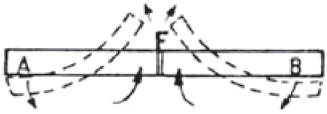
Table 1. Hypotheses tested by Georges Zbyszewski in his experiments with analogue models (adapted from Zbyszewski, G. (1947) Essai d'étude expérimentale sur les phénomènes typhoniques, *Boletim da Sociedade Geológica de Portugal*, 6, 249–252)

Hypothesis 1



The crack in the upper formations AB and the subsequent rise of the lower formations probably resulted from an uneven distribution of sediments. The sediments would induce an excessive load in A' and B' causing a weak point F. Subsidence in A' and B' would be counterbalanced by the uplift of the lower formations in F, and the consequent breakout of AB. This experiment tested the mechanism of depositional differential loading (Jackson, 1995, p. 6).

Hypothesis 2

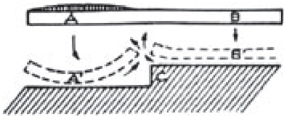


A crack of unknown origin in the upper formations AB would cause the rise of the lower formations. The lower plastic materials deeply squeezed by the weight of AB found their way out through the crack, forcing the split of the borders, and the deformation of the upper formations. This experiment tested Choffat's hypothesis.

Hypothesis 3

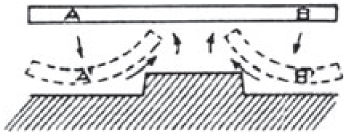
Erosion could have caused a depression from which a weak point in the upper formations AB originated. With time, a valley would form and the pressure exerted by the lower formations could lead to a crack, which allowed them to rise, and induced the deformation of AB. This experiment tested the mechanism of erosional differential loading (Jackson, 1995, p. 6).

Hypothesis 4



The existence of a step in the bedrock would be the origin of the weak point C, just above the bedrock irregularity. Subsidence in A' would lead to the deformation of AB, and a crack at C allowed the lower formations to rise.

Hypothesis 5



The existence of a horst in the bedrock, which penetrates through the lower plastic formations, is admitted. The pressure caused upon them by the upper formations AB would have caused a crack on each side of the horst, allowing the lower formations to rise.

Hypothesis 6

Contrary to the former hypotheses, in this one the pressure exerted is horizontal. Consequently, the upper formations AB would fold, and the lower plastic materials would move and rise to the top of the anticlines formed during the process. This experiment tested a hypothesis similar to the one suggested by Freire de Andrade.

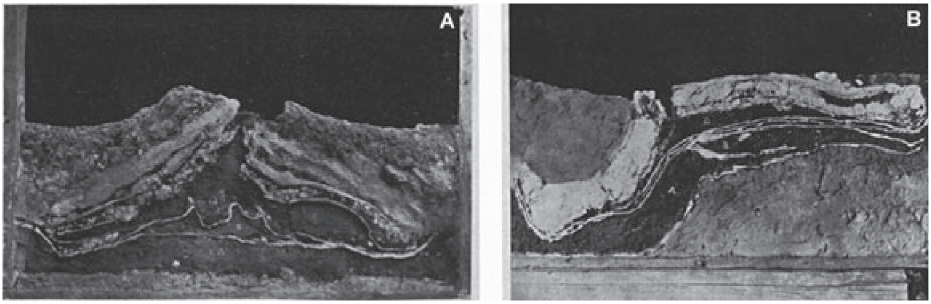


Fig. 2. Photography of two of the results obtained in Georges Zbyszewski experiments with analogue models: hypothesis 2 on the left and hypothesis 4 on the right (adapted from Zbyszewski, G. (1947) Essai d'étude expérimentale sur les phénomènes typhoniques, *Boletim da Sociedade Geológica de Portugal*, 6, planches I and II).

the models was based on the combination of various sources of data with the theoretical content of each one of the hypotheses about the origin of the typhonic valley, and therefore was not entirely dependent neither on the former nor on the latter component. The combination of these factors was also decisive for giving a certain degree of autonomy to the models. Besides, the contribution of factors such as an adequate choice of analogue materials by Zbyszewski must also be credited. It was that autonomy together with the representative value of the models that made the manipulation of structures and geological processes during the experiments possible, allowing Zbyszewski to choose between competing hypotheses.

However, Zbyszewski was well aware of the methodological limitations presented by the use of analogue models in geological research; he mentions scaling problems, the possibility that the results obtained might not be sufficiently clear, and emphasizes the need to always confront experimental results with data obtained from geological fieldwork, geophysics or drilling. These concerns are identical to those of most geologists regarding the use of analogue models in experimental geology (Oreskes, 2007, p. 95).

Zbyszewski's work is also an example of the combination of two traditional approaches in geology: the historical and the causal ones (Laudan, 1982, pp. 7–13; Laudan, 1987, pp. 1–7). It indicates that the difference between the two approaches is rather a conceptual one than a real difference and that geologists can proceed with their work by simultaneously taking the two approaches into consideration. Geologists may develop causal theories by generalizing from the chronicle of past events and they can also reconstruct the history of the Earth by using contemporary causal theories, reinforcing both historical and causal approaches in geology.

Georges Zbyszewski was the first geologist in Portugal to perform experiments with analogue models but his experiments were closer to those performed by the pioneers of geological modelling than to those that were then being carried out at foreign laboratories, in particular the experiments associated with diapiric/salt tectonics (Jackson, 1995, pp. 5–10). In fact, it is possible to say that at the time tectonics did not exist in Portugal as a specialized branch of geology (Ribeiro, 1992, p. 965). Most Portuguese geologists were generalists; the study of tectonics was one among their many interests and was usually pursued as part of broader regional geological studies. This was the case for Zbyszewski's research on the typhonic valley; it was part of a wider study on the geology of the Caldas da Rainha region, because there was interest in its potential mineral resources (Zbyszewski, 1947, p. 240). The use of analogue models was a side effect of Zbyszewski's work as a geologist for the PGS, a public institution whose main goal was to survey mainland Portugal, so that national mineral resources could be discovered and used by the Portuguese State in its pursuit of industrialization. Experimental geology was definitely not considered a priority in the context of the work of the PGS, and so the use of analogue models was not perceived as a precious instrument to be used for future geological research. It was a device that was used only because it was useful in the context of Zbyszewski's geological research at the time. Zbyszewski needed to know how the typhonic valley was formed, so that he could reconstruct the geological history of the region, and he was convinced that the use of analogue models was the most appropriate way to help him solve the problem. However, all his work was oriented towards one goal: to find mineral resources for the sake of the nation.

It may appear strange that Georges Zbyszewski carried out experiments with analogue models in a context in which there was no tradition of this type, nor, by the way, any tradition of experimental geology whatsoever. It must be kept in mind, however, that when Zbyszewski performed his experiments he had been living in Portugal on a permanent basis for only 6 years. His initial geological practice had been developed in France, where he had been working under the supervision of Jacques Bourcart (1891–1965) in the laboratory of physical geography and dynamic geology at the University of Paris. At this laboratory, Zbyszewski met French geologists like Alfred Lacroix (1863–1948), Léon Bertrand (1869–1947), and Charles Jacob (1878–1962) (Teixeira, 1984a, pp. 14 and 15; Ribeiro, 1984, p. 56; Zbyszewski, 1984, pp. 45–54). As indicated by its very name and confirmed by various Portuguese scientists who have worked there—geologist Carlos Teixeira (1910–1982) and geographers Orlando Ribeiro (1911–1997) and Antonio Medeiros-Gouvêa (1900–1972)—the research developed in the laboratory had a markedly dynamic and causal perspective.[12] Boucart—who was also the supervisor of Zbyszewski's doctoral thesis—had a particularly dynamic perspective on geology, developing much of his research along the lines of the hypothesis of continental flexure that he had himself proposed, and to which Zbyszewski adhered for some time (Gullcher, 1966, pp. 304–306; Ribeiro, 1984, pp. 56–59; Ribeiro, 2003, pp. 87).

In this way it becomes apparent that the construction and use of analogue models by Zbyszewski was part of a characteristic 'metaphysics' which existed at the French laboratory, a culture that he shared and kept in his geological practice. Furthermore, the literature mentioned by Zbyszewski in his works published on the typhonic valley show that he was well aware of the importance that analogue modelling had gained in salt tectonics research. The combination of these two factors, plus the fact that Zbyszewski possessed a relatively high degree of freedom in terms of research options at the PGS, probably provided him with the necessary conditions to idealize and carry out his experiments with analogue models.[13]

8. *Conclusion: A Bursting Landscape in the Middle of Nowhere*

The experiments with analogue models performed by Georges Zbyszewski had as their main goal the investigation of the factors underlying the origin and formation of the typhonic valley, by choosing one of several hypotheses. The use of analogue models for this specific endeavour was particularly significant; their high representative value and considerable degree of autonomy allowed their manipulation during the course of experiments and enabled Zbyszewski not only to choose between competing hypotheses on the origin of the typhonic valley, but also to reconstruct its geological history. The analogue models created, built and explored by Georges Zbyszewski functioned simultaneously as instruments for the exploration of the hypotheses and as mediating agents between them and the world (Morgan and Morrison, 1999b, pp. 10–37). However, Zbyszewski's awareness of the methodological limitations associated with the use of analogical models, led him to take into account data obtained by other geological procedures, in particular fieldwork.

Zbyszewski's precautions can be understood in the context of the methodological concerns regarding the use of analogue models elucidated by Oreskes. They can also be an indication that Zbyszewski was not entirely convinced of the importance of experiments in geological practice, thus corroborating Newcomb's ideas that many geologists do not consider experimental geology a distinctive feature of this scientific discipline. In fact, the use of analogue models by Zbyszewski did not leave traces in the country's geological practice. Afterwards, Georges Zbyszewski never used analogue models in his investigations, nor did he conduct any more work in the context of experimental geology. As time went by, Zbyszewski seems to have forsaken the 'metaphysics' underlying his earlier geological practice, probably the source of his experiments with analogue models; instead he began to develop his geological research according to a more historical approach. This turn probably occurred not only because of the nature of his work at the PGS, but also as an outcome of Zbyszewski's distance from the international geological community, which made him less familiar with updated causal theories.[14]

Besides, Zbyszewski was the only geologist working at the PGS until 1955, so there was no one to learn from him and further develop the use of experimental geology with analogue models. In other words, there were no conditions for establishing a research school in experimental geology at the PGS, because experimental geology was not considered a priority, in the context of the production of geological mapping, which was one of the main aims of the PGS.

In addition, the scientific relationships between the PGS and the universities were scarce and unilateral at the time: professors and researchers from universities were appointed scientific collaborators of the PGS but geologists from the institution did not teach at the university. There was no way Zbyszewski could share his knowledge on analogue models; a research school on experimental geology applied to tectonics was to develop only about 40 years later, in the 1980s. By then, the laboratory of experimental tectonics (LATEX)[15] had been created at the University of Lisbon by a group of Portuguese geologists who specialized in tectonics and it gave rise to a research school in experimental tectonics in the context of which the use of analogue modelling became relevant. The founders of LATEX ignored Zbyszewski's experiments when they created the laboratory. Although they consider him the 'founding figure' of their area of research, Zbyszewski did not have any direct influence on the establishment of LATEX.[16] Thus, perhaps a more suitable title for this paper would be: 'A bursting landscape in the middle of nowhere. . .'

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NOTES

1. See for instance: Good (1998), Burchard (1998), Dawson (1992), Fritscher and Henderson (1998).
2. The word typhonic has its origin in Greek mythology: Typhon was the son of Saturn and the Earth, and during his birth he violently ripped the Earth's flanks. Alexandre Leymerie (1801–1878) was probably the first author to use the word to name a group of lifted volcanic rocks and the deformed sediments surrounding them.
3. Diapirism is the mechanism by which intrusive bodies of buoyantly upwelling rock move laterally and vertically in the subsurface.
4. The Hettangian is the first stage of Lower Jurassic; it makes the transition between the Triassic and the Jurassic.
5. Orogeny is the process of mountain formation in the earth's crust.
6. Zbyszewski believed that the existence of large horizontal movements was quite improbable in the context of Portuguese tectonics, but he admitted that the ancient substratum—which was broken, divided into pieces and displaced—could have been affected by some kind of pressure leading to the compartments moving. This might have set off either vertical or horizontal movements, which in turn would lead to the deformation of the upper formations.

7. During the 1920s and 1930s, the two main hypotheses proposed by the international geological community to explain the emplacement of diapiric structures were buoyancy—where vertical forces caused by the weight of overlying strata predominated—and regional contraction, with lateral forces being responsible for the mechanism.
8. The way materials behave in terms of deformation when subjected to some kind of force.
9. Authors defending the semantic perspective on models: Giere (1988) and Suppe (1989). Authors defending the analogical conception of theorie's perspective on models: Hesse (1966) and Gooding (1990).
10. The first important theory on scale modelling in geology is due to M. King Hubbert. He derived a set of relations between the physical properties of the model system and those of the system modelled, based on assumptions about proportionality between the two systems. In addition, there was the condition that the materials should have a similar structure and behaviour.
11. For the use of visual language in geology, see, for example, Rudwick (1976) and Howarth (2002).
12. Teixeira (1984a, pp. 15–17), Ribeiro (1984, p. 57), Zbyszewski (1984, pp. 46–49) and Ribeiro (2003, pp. 87–89).
13. Zbyszewski was the only geologist at the PGS during the 1940s and the 1950s, where he had to do a great variety of geological work and research. However, as long as Zbyszewski accomplished his institutional tasks, he was free to carry out whatever kind of research he wished, to work with other geologists from outside the PGS, and to publish wherever he chose to. This can be noticed in Zbyszewski's bibliography and was confirmed by the oral testimony of Portuguese geologist António Ribeiro, who worked with Zbyszewski at the PGS during the 1960s and the 1970s.
14. Oral testimony by the Portuguese geologist António Ribeiro.
    Most Portuguese geologists were aware—even if sometimes with some delay—of what was going on in international geological research. They used to attend the meetings of the International Geological Congress and other international geological meetings. However, when Zbyszewski decided to live in Portugal, he chose a country that lived under a dictatorship. The Portuguese regime lived in a certain autarchy and it was not easy to leave the country even temporarily. Although geologists were not really isolated from their foreign peers, international contacts were certainly less easy and less frequent than they could have been if Portugal had been a democracy.
15. Today, this research centre is called the Laboratory of Tectonophysics and Experimental Tectonics (*Laboratório de Tectonofísica e Tectónica Experimental*) or LATTEX.
16. Oral testimony by the Portuguese geologist Paulo Fonseca, one of the co-founders of LATEX.

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